

# The KX method for producing K-band flux-limited samples of quasars

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## ABSTRACT

The longstanding question of the extent to which the quasar population is affected by dust extinction, within host galaxies or galaxies along the line of sight, remains open. More generally, the spectral energy distributions of quasars vary significantly and flux-limited samples defined at different wavelengths include different quasars. Surveys employing flux measurements at widely separated wavelengths are necessary to characterise fully the spectral properties of the quasar population. The availability of panoramic near-infrared detectors on large telescopes provides the opportunity to undertake surveys capable of establishing the importance of extinction by dust on the observed population of quasars. We introduce an efficient method for selecting K-band, flux-limited samples of quasars, termed “KX” by analogy with the UVX method. This method exploits the difference between the power-law nature of quasar spectra and the convex spectra of stars: quasars are relatively brighter than stars at both short wavelengths (the UVX method) and long wavelengths (the KX method). We consider the feasibility of undertaking a large-area KX survey for damped Ly $\alpha$  galaxies and gravitational lenses using the planned UKIRT wide-field near-infrared camera.

**Key words:** quasars: general – quasars: absorption lines – gravitational lensing – methods: observational

## 1 MOTIVATION

More than three decades since the discovery of quasars the question of whether our knowledge of the quasar population is affected significantly by dust extinction, within host galaxies or galaxies along the line of sight, remains controversial. Obscuration by tori or other non-spherical components forms a key element of unified schemes for active galactic nuclei (AGN). Similarly, while estimates of the extinction optical depth through the discs of spiral galaxies differ, a number of gravitationally lensed quasars and AGN provide unambiguous evidence that extinction within the deflector or host galaxies affects our view of the sources. However, it is not clear if obscuration by dust merely perturbs our view, increasing the overall quasar space density, or the frequency of a particular quasar sub-type, by a factor two or less, or, whether objects in existing quasar surveys represent only a small fraction of the (unobscured) population.

Much discussion concerning obscured quasars has focussed on whether such objects, with their spectral energy distributions (SEDs) steepened by the effects of reddening by dust, would be detectable using a particular quasar iden-

tification technique, such as slitless spectroscopy or multi-colour selection in the optical. In fact, given that most surveys for quasars rely on flux-limited samples of very limited dynamic range, the key problem is that quasars will be dimmed to the extent that they simply do not appear in the sample. Fortunately, the rapid advance in the fabrication of large near-infrared detectors means it will soon be viable to undertake surveys for quasars over large areas of sky that are much less susceptible to the effects of extinction by dust.

In this paper we introduce a method for selecting samples of quasars, flux-limited in the K band, that would include quasars whose flux has been dimmed by dust, and which may have eluded conventional optical surveys. The method is termed “KX”, by analogy with the UVX method, as it similarly exploits the difference between the power-law nature of quasar spectra and the convex spectra of stars; quasars are brighter relatively than stars at both short wavelengths (the UVX method) and long wavelengths (the KX method). In this section we review the motivation for surveys that can detect reddened quasars. In §2 we describe the method. Then, in §3 we consider the feasibility of undertak-

ing a large KX survey for damped Ly $\alpha$  galaxies and gravitational lenses using the planned UKIRT wide-field near-infrared camera.

### 1.1 Quasars and cosmology

Samples of distant quasars that are bright at optical wavelengths have proven valuable in a number of areas in extra-Galactic astronomy and cosmology. Here we focus on the use of quasars for i) charting the history of star formation with lookback time through surveys for damped Ly $\alpha$  (DLA) galaxies (Pei and Fall 1995), and ii) determining the geometry of the Universe from the measurement of the frequency of gravitational lensing (Fukugita, Futamase and Kasai 1990, Turner 1990). The effects of dust in the intervening galaxies are crucial to the interpretation of such studies. Surveys for quasars at optical wavelengths are very susceptible to extinction, because the observed passband corresponds to the rest-frame ultraviolet at moderate redshift and beyond. Utilising near-infrared wavelengths produces a significant improvement. For example, a high-redshift quasar,  $z \sim 3$ , behind a DLA system at  $z = 2.5$  with (rest-frame)  $E(B - V) = 0.2$  mag would suffer 2.8 mag extinction in the observed-frame B-band but only 0.5 mag at K. (Except where otherwise noted all extinction calculations assume an LMC-like extinction curve below  $0.33\mu$  rest-frame (Howarth 1983), the Mathis (1990) curve at longer wavelengths, and  $R_V = 3.1$ ).

#### 1.1.1 Damped Ly $\alpha$ galaxies and the Universal history of star formation

To measure the history of gas consumption by star formation in the Universe, quasars are used as background sources of light and their spectra are searched for DLA absorption lines caused by intervening clouds with a high column density of neutral hydrogen. Bright quasars are needed to provide sufficiently high signal-to-noise ratio spectra to measure the absorption line properties of the intervening gas. The frequency and column densities of the DLA absorption lines yield a direct measurement of the cosmic density of neutral gas,  $\Omega_{\text{HI}}$ , (Wolfe 1987). Since dusty DLA absorbers can be missed because the quasar will be dimmed by extinction below the flux limit chosen for the spectroscopic observations, the procedure is only valid *provided the obscuring effects of dust are taken into account*. The measured decline of  $\Omega_{\text{HI}}$  with time, corrected for the effects of dust, can be related directly to the history of star formation (under assumptions about the exchange of gas between the neutral and ionised gas phases).

Pei and Fall (1995) have made the most detailed and complete analysis of this problem. To account for the effects of dust they made the simplifying assumption that all absorbers at the same redshift have the same dust-to-gas ratio. By including in their treatment a term specifying the mean metallicity,  $Z(z)$ , of the DLA absorbers they successfully computed models of cosmic star formation and chemical enrichment that account for the redshift dependence of the measured  $\Omega_{\text{HI}}$ , while allowing, in a self-consistent manner, for the selection effect of the increasing obscuration due to dust as star formation progresses. The outputs of the cal-

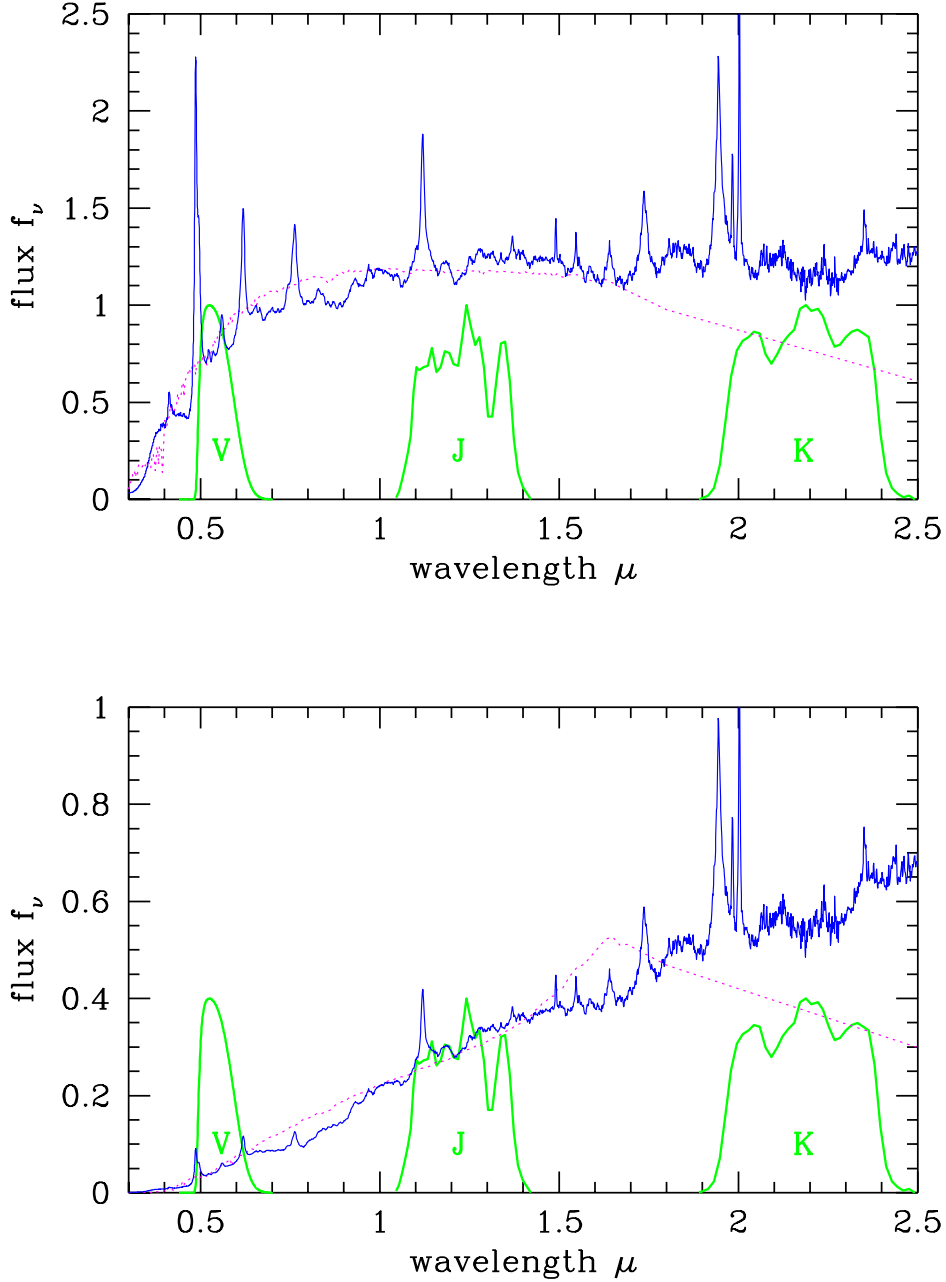
culations are the evolution with redshift of the true  $\Omega_{\text{HI}}$ , the rate of star formation and the metallicity of the gas.

Pei and Fall confirmed that a modest range in the dust-to-gas ratio in DLAs at any redshift does not greatly alter their results. The actual range in the dust-to-gas ratio is difficult to measure, because any dusty DLAs will have been missed. Boissé et al (1998) provide a discussion of this issue and present evidence for a bias against dusty DLAs in the current samples. Therefore, it appears at least possible that the actual range in dust-to-gas ratios is large, and that many dusty DLAs have evaded the census, which would mean that our picture of the history of gas consumption is incorrect. A large sample of DLAs selected from spectra of a sample of quasars flux-limited in the K-band would provide the data for a proper treatment of the effects of dust.

#### 1.1.2 Gravitational lenses and the value of the cosmological constant

Fukugita et al (1990) and Turner (1990) show that for flat geometries as predicted by inflation,  $\Omega_{\text{matter}} + \Omega_{\Lambda} = 1$ , the probability that a quasar is gravitationally lensed is more than an order of magnitude greater for large values of the cosmological constant  $\Lambda$  ( $\Omega_{\Lambda} \sim 1$ ) than for small values ( $\Omega_{\Lambda} \sim 0$ ). Therefore, counting the fraction of gravitational lenses in a sample of quasars is in principle a powerful method for establishing the global geometry of the Universe. In practice the calculations necessary are quite involved (e.g. Maoz and Rix 1993, Kochanek 1996) but the conclusion of most analyses has been that the statistics of lensed quasars and AGN are inconsistent with a large value for the cosmological constant. For example Falco, Kochanek and Munoz (1998) provide the  $2\sigma$  limit  $\Omega_{\Lambda} < 0.62$ . However, in a recent study, Chiba and Yoshii (1999) found a best fit value  $\Omega_{\Lambda} \sim 0.7$ . The difference between these results is largely explained by uncertainties in the properties of the lensing galaxies (velocity dispersions, space densities), which probably prohibit a definitive answer until they are better established. Another potentially significant source of uncertainty is our lack of knowledge of the evolution of massive galaxies, in particular their merging history.

All calculations agree that massive early-type galaxies dominate the lensing cross-section. Locally, most early-type galaxies contain little dust so the existence of a number of highly reddened, lensed, quasars (e.g. MG0414+0534, Lawrence et al 1995) is something of a puzzle. The reddening may be intrinsic to the quasar but reddening due to dust in the lensing galaxy is also a possibility. The lensing cross-section of massive spiral galaxies may have been underestimated, or early-type galaxies at redshifts  $0.5 < z < 1.0$  could be substantially dustier than those seen locally. In either case if a population of dusty galaxies contributes significantly to the lensing cross section at these redshifts, then samples of gravitational lenses drawn from optical samples of quasars would be significantly incomplete, producing an underestimate of the value of  $\Omega_{\Lambda}$ . The uncertainty over the effect of dust on the lensing statistics could be greatly reduced by searching for gravitational lenses in a K-band, flux-limited sample of quasars.



**Figure 1.** Comparison of the optical-to-near-infrared spectral energy distribution of quasars and stars, illustrating the principle of the KX method. The flux scale is arbitrary, but the same for both plots. Each plot shows an extended version of a composite quasar spectrum (Francis et al 1991) and a star (Buser and Kurucz 1992, Kurucz 1979) with similar V-J colour. The V, J and K filter transmission curves are overplotted. The upper plot shows the spectra of an unreddened  $z = 3$  quasar (solid line) and an early K star (dotted line). The K excess is clearly visible. The lower plot shows the same quasar experiencing rest-frame extinction of  $E(B - V) = 0.3$  in an intervening system at  $z = 2.5$ . The spectrum of an early M-star, having a similar V-J colour, is shown for comparison. Again, a substantial K excess is apparent, demonstrating the effectiveness of the KX method in identifying both unreddened and reddened quasars.

## 1.2 Red quasars

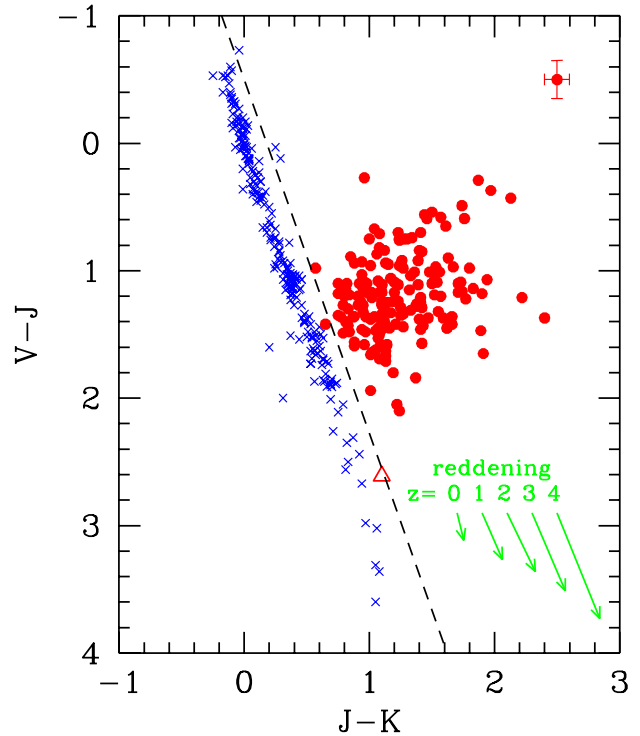
Quasars have been detected at all wavelengths from gamma-rays to radio waves and they produce a significant fraction of their energy output over many decades in frequency. Furthermore, the proportion of the total energy radiated at different frequencies varies substantially among the quasar population. A deep survey at, say, optical wavelengths could miss quasars where the bulk of the energy is emitted in, say, the far-infrared, and *vice versa*. To characterise the bolometric energy output of the quasar population it is necessary to undertake surveys at several wavelengths that include significant contributions from the different components that make up the quasar spectrum (Hewett and Foltz, 1994). The importance of undertaking surveys at multiple frequencies is illustrated by Webster et al (1995), who claim that, due to the effects of extinction, the bulk of the quasar population has gone undetected in optical surveys. This conclusion is nevertheless controversial (e.g. Benn et al 1998) and surveys for quasars in the K band would provide a direct test of the hypothesis by establishing the fraction of reddened quasars that are under-represented in optical samples.

## 2 THE KX METHOD

The KX method exploits the fact that, by comparison with a star with the same V-J colour, quasars are redder in J-K so the two populations separate in the two-colour diagram for point sources. The upper plot in Figure 1 shows the spectrum of a quasar of redshift  $z = 3$  and the V, J and K filter transmission curves. Overplotted is the spectrum of an early K-star, chosen because its V-J colour is similar to the quasar. The excess flux of the quasar in the K band, amounting to  $\sim 0.5$  mag, is evident. The lower plot in Figure 1 shows the effectiveness of the KX method in detecting also reddened quasars. The quasar spectrum of the upper plot has been reddened as appropriate for an absorbing cloud at  $z = 2.5$  with rest-frame  $E(B - V) = 0.3$ . Overplotted is the spectrum of an M-star, chosen for the match in V-J colour. The excess flux of the quasar in the K band is again clearly visible.

The KX method in practice is illustrated in Figure 2 which is a VJK two-colour diagram showing the location of Galactic stars ( $\times$ ) and quasars ( $\bullet$ ). The stellar photometry was taken from the list of bright UKIRT standards for which the quoted photometric errors are 0.015 in J-K and 0.05 in V-J. The VJK quasar photometry (Hewett et al, in preparation) consists of 152 quasars,  $0.2 < z < 3.4$ , from the Large Bright Quasar Survey (Hewett, Foltz and Chaffee 1995) and 20 quasars,  $2.0 < z < 3.4$ ,  $16.5 < V < 19.5$ , used in studies of DLA absorbers (e.g. Pei, Fall and Bechtold 1991; Table 1). For clarity, individual error bars are not plotted but the photometric errors are nearly all  $\leq 0.15$  mag in each colour. The V photometry was not in general acquired at the same epoch as the infrared magnitudes and an additional scatter of  $\sim 0.1$  mag, due to intrinsic photometric variability in the quasars, will be present in the V-J colour for many of the objects.

A possible selection boundary,  $J - K > 0.36(V - J) + 0.18$ , discriminating the quasars from the sequence of stars is shown by the dashed line. All but one of the 172



**Figure 2.** VJK two colour diagram for stars ( $\times$ ) and quasars ( $\bullet$ ) illustrating the KX technique. The stellar photometry was taken from the list of bright UKIRT standards at [http://www.jach.hawaii.edu/UKIRT/astronomy/calib/bright\\_stds.html](http://www.jach.hawaii.edu/UKIRT/astronomy/calib/bright_stds.html). The quasar photometry consists of our own measurements of 172 quasars, redshifts  $0.2 < z < 3.4$ , magnitudes  $B < \sim 19$ , representative of objects identified using optical survey techniques. Photometric errors for the stars are similar to or smaller than the symbol size while representative errors for the quasars are shown at top right. Reddening vectors are shown for 5 different redshifts of the absorber and are computed for rest-frame  $E(B - V) = 0.1$  using the LMC extinction curve. The possible selection boundary, indicated by the dashed line, is  $J - K > 0.36(V - J) + 0.18$ . The reddening vectors are approximately parallel to the selection boundary, so the effectiveness of the method is largely insensitive to the effects of reddening provided a quasar is included in the flux-limited sample. The triangle marks a quasar of redshift  $z = 4.5$  discussed in the text.

quasars plotted,  $z < 3.4$ , lie to the right of the selection line shown. The quasar to the left of the selection line is LBQS1212+1445, a broad absorption line object at redshift  $z = 1.63$ . The K-photometry for this object in the UKIRT dataset that provides many of the infrared magnitudes shown in Figure 1 is 0.4 mag fainter than an observation made with the Multiple Mirror Telescope (MMT). While the use of the MMT K-magnitude would move the object 0.4 mag rightward into the well populated portion of the plot there is no indication of anything amiss with the UKIRT K-band magnitude and for consistency we have plotted the J-K colour from the UKIRT observations.

Also shown in Fig. 2 are the reddening vectors for an intervening absorber with an LMC extinction curve, of rest-frame  $E(B - V) = 0.1$ , at five different redshifts. Each vector

runs approximately parallel to the stellar locus, so reddened quasars can also be detected by this method. <sup>\*</sup> Given adequate signal-to-noise ratio,  $\sim 10$ , in the estimate of the object colours the KX method should identify nearly all quasars found in optical samples, whether reddened or not, above the K-band flux limit.

Application of the KX method in practice will require good quality images in order to separate point sources from galaxies, because the colour distribution of faint galaxies overlaps that of quasars (this is also true of the UVX method). A potential difficulty which we have not addressed is the brightness of the quasar host galaxy. The contribution to the total flux of the host galaxy will in general be larger in the K band than in the optical so lower luminosity quasars might be excluded from a catalogue of point sources. However, this is not an issue for the bright flux levels considered in §3.

The VJK combination is so effective because the spectral energy distribution of stars with similar V-J colours to quasars (principally those of spectral types K and M) turn over in the H band (Fig. 1). The J and K bands straddle the break point, providing the discriminatory power of the technique, so utilising H-band magnitudes in place of J or K is not viable. A limit to the effectiveness of the KX method using V, J, and K passbands occurs at redshifts  $z > 3.5$  where absorption by the Ly $\alpha$  forest is present over much of the wavelength range included in the V-filter. Quasars start to become redder in V-J, moving vertically in the VJK diagram and approaching the stellar locus. In Figure 2 the triangle marks the colours of a quasar of redshift  $z = 4.5$ , which lies below the colour selection boundary because of this absorption. Substituting the R or I filter for V would extend the effectiveness of the KX method to redshifts beyond  $z = 4$ .

At the end of this section we reemphasise the difference between the effects of reddening and extinction on the completeness of quasar surveys. Some optical survey methods, including the multicolour method and emission-line searches (but excluding the UVX method), are also largely insensitive to reddening. The advantage of the KX method over all optical survey methods is the reduced extinction in the K band, rather than simply the ability to find reddened quasars, i.e. a much larger fraction of quasars suffering extinction will be included in the K-band, flux-limited sample.

### 3 A KX SURVEY WITH THE UKIRT WIDE-FIELD NEAR-INFRARED CAMERA

The proposed UKIRT wide-field near-infrared camera will image 0.2 square degrees per exposure. One of its goals is a moderately deep survey over a substantial fraction of the area of the Sloan Digital Sky Survey (SDSS) accessible by UKIRT, i.e. thousands of square degrees, to a depth of  $K=19$  with a signal-to-noise ratio of  $\sim 10$ . Such a survey would contain many thousands of quasars. Here we consider the

effectiveness of this survey for finding damped Ly $\alpha$  galaxies and gravitational lenses, especially examples where the background quasar had been dimmed by dust in the intervening galaxy.

#### 3.1 Damped Ly $\alpha$ galaxies

A survey for DLAs requires samples of high-redshift  $z \gtrsim 2$  quasars, since for ground-based spectroscopy DLAs are only detectable at  $z > 1.8$ . The number of DLAs catalogued in the literature is approaching 100. Therefore, to provide a substantial advance, a survey that produces more than 300 DLAs is desirable. For a given survey area we can compute the K-band flux limit that will provide sufficient quasars to produce a sample of DLAs of this size. We can then verify that this flux limit is sufficiently bright, say  $R \leq 20$ , to allow high-resolution spectroscopy on an 8-metre class telescope for the measurement of the absorber metallicities.

For the calculation we take an area of 4000 square degrees over a region in common with the SDSS. An advantage of covering the SDSS area is that low-resolution spectra of most of the bright KX-selected quasar candidates will exist in the SDSS database. Taking the quasar luminosity function of Warren, Hewett and Osmer (1994) we can compute the surface density of high-redshift quasars as a function of R magnitude. We then convert to K assuming a mean colour of  $R-K=2.2$ . We then estimate the number of DLAs by assuming a line density  $dn/dz = 0.055(1+z)^{1.15}$  (Wolfe et al. 1995) and supposing that DLAs can be detected from the quasar emission redshift down to  $z = 1.8$ .

Over 4000 square degrees, to  $K=16.0$ , we estimate there would be  $\sim 2300$  high-redshift,  $z > 2.2$ , quasars with over 500 detectable DLAs. If there is a serious bias in existing optical samples of DLAs the number of DLAs detected will be larger. Since  $K=16.0$  corresponds to  $R=18.2$  for a typical quasar, quasars that are substantially reddened,  $\lesssim 2$  mag in the optical, would still be bright enough for high-resolution spectroscopic follow-up.

An alternative strategy could be to use radio-selected quasars to undertake a survey for DLAs unbiased by extinction due to dust. There are two disadvantages to this approach. Firstly there are insufficient high-redshift radio quasars to yield a sample of DLAs of the size envisaged here. Secondly, a significant fraction of the quasars will be very faint in the optical, precluding high-resolution spectroscopy, yet it is essential to survey the spectra of all the quasars for the sample to be unbiased. Nevertheless, any subset of quasars suffering very large extinctions that still elude the K-band flux-limited selection could be identified in a radio survey.

#### 3.2 Gravitational lenses

Excluding lensing by galaxy clusters, there are currently only some 40 examples of strong gravitational lensing known (<http://cfa-www.harvard.edu/castles/>). For the same survey for bright quasars considered above,  $K < 16.0$ , counting quasars of all redshifts there will be over 10000 quasars over the 4000 deg<sup>2</sup> survey area. For a typical quasar colour  $V-K=2.5$  the survey magnitude limit is equivalent to  $V=18.5$ . Therefore the apparent magnitudes of the quasars will be

<sup>\*</sup> We checked that this conclusion also holds true for the UV extinction curves for the SMC (Prévot et al. 1984) and for the Galaxy (Mathis 1990). In the case of the SMC at high redshift the reddening vectors are a little steeper than those for the LMC, while for the Galaxy the vectors are a little shallower.

similar to the apparent magnitudes of the quasars observed in the HST snapshot survey (Maoz et al 1993) which have  $V = 18.0 \pm 0.8$ . There are five cases of gravitational lensing amongst the 502 quasars imaged in the snapshot survey. Because the apparent magnitudes are similar we can use the results of the snapshot survey to estimate the number of lenses in the UKIRT survey by assuming that 1% of the quasars are lensed (the fraction of lenses in a sample depends on the sample depth because of magnification bias). Therefore the UKIRT survey should produce roughly 100 gravitational lenses. The number of lenses detected could be larger than 100 if bias due to dust is important.

It is unlikely that the image quality achieved in the survey will be good enough to detect examples of gravitational lensing where the image separation is less than 0.5 arcsec. Sensitivity to separations as small as 0.2 arcsec could be achieved by later imaging all the bright quasars using adaptive optics. The fraction of lenses in a K-selected sample could be increased in two ways. Firstly, a sample of similar size could be obtained by surveying a larger area of sky but to a brighter magnitude limit, thereby increasing the magnification bias. Alternatively, follow-up high-resolution imaging could be limited to quasars of high redshift, since the probability that a quasar is lensed increases with redshift.

The interpretation of a survey for gravitational lenses requires knowledge of the quasar luminosity function at magnitudes fainter than the search limit, since the lensed quasars have been magnified. A potential drawback of the KX method is contamination of the sample of candidate quasars at faint magnitudes by compact galaxies that morphologically cannot be distinguished from stars. Nevertheless, at these fainter magnitudes where the surface densities are higher it will be feasible to measure the quasar luminosity function based on spectroscopic surveys of complete flux-limited samples (i.e. with no colour or morphological selection) using multi-object spectrographs. One advantage of K-band surveys for gravitational lenses over radio surveys such as CLASS (Jackson et al 1998) is the ease with which the redshift distribution of the unlensed source population can be measured.

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## REFERENCES

- Benn C R, Vigotti M, Carballo R, Gonzalez-Serrano J I, Sánchez S F, 1998, MNRAS 295, 451  
 Boissé P, Le Brun V, Bergeron J, Deharveng J-M, 1998, A&A 333, 841  
 Buser R, Kurucz R L, 1992, A&A 264, 557  
 Chiba M, Yoshii Y, 1999, ApJ 510, 42  
 Falco E E, Kochanek C S, Munoz J A, 1998, ApJ 494, 47  
 Francis P J, Hewett P C, Foltz C B, Chaffee F H, Weymann R J, Morris S L, 1991, ApJ 373, 465  
 Fukugita M, Futamase T, Kasai M, 1990, MNRAS 246, 24P  
 Hewett P C, Foltz C B, 1994, PASP 106, 113

- Hewett P C, Foltz C B, Chaffee F H, 1995, AJ 109, 1498  
 Howarth I H, 1983, MNRAS 203, 301  
 Jackson N, Nair S, Browne I W A, et al 1998, MNRAS 296, 483  
 Kochanek C S, 1996, ApJ 466, 638  
 Kurucz R L, 1979, ApJS 40, 1  
 Lawrence C R, Elston R, Januzzi B T, Turner E L, 1995, AJ 110, 2570  
 Maoz D, Bahcall J N, Schneider D P, Bahcall N A, Djorgovski S, Doxsey R, Gould A, Kirhakos S, Meylan G, Yanny B, 1993, ApJ 409, 28  
 Maoz D, Rix H-W, 1993, ApJ 416, 425  
 Mathis J S, 1990, ARA&A 28, 37  
 Pei Y C, Fall S M, 1995, ApJ 454, 69  
 Pei Y C, Fall S M, Bechtold J, 1991, ApJ 378, 6  
 Prévot M L, Lequeux J, Maurice E, Prévot L, Rocca-Volerange B, A&A 132, 389  
 Turner E L, 1990, ApJ 365, L43  
 Warren S J, Hewett P C, Osmer P S, 1994, ApJ 421, 412  
 Webster R L, Francis P J, Peterson B A, Drinkwater M J, Masci F J, 1995, Nature 375, 469  
 Wolfe A M, 1987, Proc Phil Trans Roy Soc 320, 503  
 Wolfe A M, Lanzetta K M, Foltz C B, Chaffee F H, 1995, ApJ 454, 698